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On the regional distribution of mitigation costs in a global cap-and-trade regime

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Abstract This paper analyzes the regional distribution of climate change mitigation costs in a global cap-and-trade regime. Four stylized burden-sharing rules are considered, ranging from GDP-based permit allocations to schemes that foresee a long-term convergence of per-capita emission permits. The comparison of results from three structurally different hybrid, integrated energy-economy models allows us to derive robust insights as well as identify sources of uncertainty with respect to the regional distribution of the costs of climate change mitigation. We find that regional costs of climate change mitigation may deviate substantially from the global mean. For all models, the mitigation cost average of the four scenarios is higher for China than for the other macro-regions considered. Furthermore, China suffers above-world-average mitigation costs for most burden-sharing rules in the long-term. A decomposition of mitigation costs into (a) primary (domestic) abatement costs and (b) permit trade effects, reveals that the large uncertainty about the future development of carbon prices results in substantial uncertainties about the financial transfers associated with carbon trade for a given allocation scheme. This variation also implies large uncertainty about the regional distribution of climate policy costs.

Abbreviations

IPCC	Intergovernmental panel on climate change
SAR	Second assessment report of the IPCC
TAR	Third assessment report of the IPCC
RECIPE	Report on energy and climate policy in Europe

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1 Introduction

Climate science indicates that substantial emission reductions are required to stabilize greenhouse gas concentrations at a level that prevents dangerous anthropogenic interference with the climate system (Fisher et al. 2007; Meinshausen et al. 2009). Policymakers in most countries, however, have been reluctant to commit to concrete actions at the scale required to meet ambitious global climate stabilization targets (Rogelj et al. 2010), chiefly because they fear adverse effects on their national economies. Therefore, sound assessments of the costs of climate policy are a highly important prerequisite for successful climate policy.

Most studies about the economics of climate change mitigation have focused on the global costs of climate stabilization (Stern 2006; Fisher et al. 2007; and references in both). However, regional costs may deviate substantially from the global average. It is widely accepted that universal, globally uniform carbon pricing is an essential element of cost-effective climate change policy (Fisher et al. 1996). This can be achieved with a global emissions trading system or a globally uniform carbon tax.

A central question determining the acceptability of an international emissions trading system for both developed and developing countries is the distribution of the costs of climate change mitigation among the world's regions. Modeling literature from the nineties (Chapters 8 and 9 of IPCC SAR, Hourcade et al. 1996; Rose et al. 1998) and subsequent research (IPCC TAR, Hourcade et al. 2001; and Chapter 3 of the most recent IPCC assessment report, Fisher et al. 2007; Gupta et al. 2007) have already addressed the regional distribution of climate policy costs. Recent studies have focused on the sensitivity of regional mitigation costs with regard to the stringency of the climate policy target (den Elzen et al. 2008), the role of technology availability (Lüken et al. 2011), the effects of trade in goods and resources (Leimbach et al. 2010a), and the effects of fragmented climate policy regimes (Clarke et al. 2009; Jakob et al. 2010). In a meta-study, Hof et al. (2008) analyzed the relative position of world regions in terms of mitigation costs across different studies and found them to be generally consistent.

The objective of this paper is to systematically analyze and compare the regional mitigation costs of three structurally different models. All three of the hybrid models used in this study are characterized by a combination of macro-economic explicitness and detail in their representations of regional energy systems. This fully integrated perspective allows us to address the following questions:

- How do the global costs of climate mitigation policy translate into regional mitigation costs?
- How does the emission permit allocation under a global-cap-and-trade agreement influence mitigation costs?
- What are other determinants of regional mitigation costs?
- How can we understand and explain differences in model results?

With the aim of understanding the differences across models, this analysis is augmented by disentangling the roles of (i) the domestic technical and economic potential for abating emissions and (ii) the direct and indirect effects of trade in emission permits. Section 2 proceeds with a description of the numerical models used and the burden-sharing scenarios considered, while Section 3 presents the results in terms of climate change mitigation costs and their regional distribution. Finally, Section 4 concludes and discusses the implications of the findings.

2 Study design

2.1 Model descriptions

This section briefly describes the three energy-economy-climate models that form the basis of this study. Jakob et al. (2009b) provide a detailed description of the models.

The WITCH model, developed by the climate change group at FEEM (Bosetti et al. 2006, 2007; De Cian et al. 2011), is a multi-region model that explicitly accounts for the non-cooperative nature of international relationships. WITCH is an inter-temporal optimization model, in which perfect foresight prevails over a long-term horizon covering the entire century. The model includes a range of traditional and advanced energy technology options, with different assumptions of their future development. The diffusion of breakthrough and yet-to-be commercialized technologies is related to the level of innovative activity and to the deployment of the technology itself, once it is developed. The model considers two breakthrough energy options that provide an alternative to nuclear power in the electric sector and to oil in the non-electric end-use sector. The cost of technologies that are already available, such as wind turbines and solar photovoltaic panels, is described by a learning curve. Finally, improvement in energy efficiency is also endogenous and triggered by dedicated R&D investments. Regional stocks of energy efficiency knowledge are linked via international spillovers.

The global multi-region model, ReMIND-R (Leimbach et al. 2010a, b; Bauer et al. 2011), was developed at the Potsdam Institute for Climate Impact Research (PIK). It is an energy-economy-climate model that, like WITCH, maximizes welfare in a full inter-temporal optimization and assumes the perfect foresight of agents. ReMIND-R incorporates a detailed description of energy carriers and conversion technologies, including a wide range of carbon-free energy sources. Among the models used in this study, ReMIND-R is the only one to represent the possibility of generating negative emissions via bioenergy use with CCS. ReMIND-R represents trade in primary energy resources, emission allowances, and a generic consumption good. Trade deficits and surpluses effectively give rise to an international and inter-temporal capital market, which facilitates low-carbon investments in capital-scarce economies. Therefore, the model captures a large spectrum of macro-economic effects of climate policy including shifts in trade patterns and feedbacks on investment behavior. By embedding a technologically detailed representation of the energy sector within the macroeconomic system, ReMIND-R combines the major strengths of bottom-up and top-down models.

IMACLIM-R, developed by CIRED (Crassous et al. 2006; Sassi et al. 2010; Waisman et al. 2011), is a recursive computable general equilibrium model that captures explicitly the underlying mechanisms driving the dynamics of technical parameters, structural change in demand for 12 energy and non-energy goods, and micro- as well as macro-economic behavioral parameters. The model considers open economies with international trade of all goods and CO_2 permits. A major feature of IMACLIM-R is the partial use of production factors (representation of excess capacities, labor rigidities, and unemployment) due to sub-optimal investment decisions resulting from the interplay between inertia, imperfect foresight, and 'routine' behaviors. This allows for the distinguishing between potential and real economic growth, and more specifically, capturing the transitory costs that result from policies and other shocks affecting the economy. In IMACLIM-R, climate policies contribute to remedying market failures related to the myopic behaviors of economic agents; for instance, improvements in energy efficiency or infrastructure policies are profitable in the long-term, but are avoided in the absence of climate policies. This property can result in a "bi-stability" in the sense that initially large efforts are required to move the system from its current path (i.e. fossil-based) to an alternative one (i.e. low-carbon), but little extra effort is required once the endogenous technical changes and infrastructure adjustments come to bear. The dead-weight losses of economic output resulting from carbon pricing are higher, especially over a transition period, than in models with perfect expectation, flexibility, and full use of production factors, such as ReMIND-R or WITCH. In IMACLIM-R, these dead-weight losses are strongly affected by assumptions on infrastructure policies, which can help to control the long-term dynamics of energy demand. This is also true for labor and educational polices, which reallocate the labor force more efficiently and quickly.

In order to disentangle the effects that are specific to IMACLIM-R, two sets of climate policy scenarios are presented: In the first set (IMACLIM-REF), a pessimistic setting is chosen in which no complementary infrastructure and labor policies were assumed, and the revenues from the carbon market are assumed to be recycled directly to the households. In both the baseline and the policy scenarios of the 2nd set (IMACLIM-AP), infrastructure and labor policies are assumed to be in place that increase the flexibility of the economy. In the case of climate policies, it is assumed that carbon market revenues are used to reduce the costs of labor, thus further decreasing dead-weight losses.

For the sake of better comparability of the model results, the assumptions on the future development of population growth and global economic output are harmonized across the three models (Jakob et al. 2009a). In addition, the fossil resource assumptions are benchmarked. All the models assume the abundant and cheap availability of coal, while oil and gas are assumed to be relatively scarce.

By contrast, the models incorporate different visions of the availability and development of energy conversion technologies (Luderer et al. 2011; Tavoni et al. 2011), as well as of the mechanisms of macro-economic development.

All the models group countries into a limited number of regions (11–12). Jakob et al. (2009b) provide a detailed overview of the regional definitions used in the RECIPE models. To derive meaningful conclusions on a regional scale, we aggregated results from each model into six "macro-regions," which are similar (albeit not identical) across the models. They include the European Union (EUR), the United States of America (USA), Rest of Annex-I (R-AI), China (CHN), India (IND), and Rest of non-Annex-I (R-nAI). The time horizon considered is 2005–2100, and the models are calibrated to the base year 2005.

For this analysis, we use the difference macro-economic consumption relative to baseline levels as a proxy for the mitigation costs experienced by a region. As shown in section 3.4, these total mitigation costs can be decomposed into a sum of domestic abatement costs and effects related to emissions trading.

2.2 Scenario design

The climate policy scenarios–with different burden sharing schemes–considered in this paper aim to stabilize atmospheric CO_2 concentrations at 450 ppm. This study does not account for non-CO_2 greenhouse gases, and exogenous pathways are used for land use emissions. All four policy scenarios assume that a global carbon market is established, thus creating full where-flexibility in the mitigation effort. ReMIND-R prescribes a constraint on atmospheric CO_2 concentrations explicitly in the model formulation. WITCH prescribes an efficient time-variant cap on global emissions that is consistent with the 450 ppm target. In the IMACLIM-R scenarios, the climate policy target is implemented via a carbon price trajectory, which allows for meeting an emissions trajectory that is identical in the four climate policy scenarios and is similar to the ReMIND-R and WITCH trajectory.

While they observe the same climate constraint, the four scenarios differ with respect to the distribution of emission permits among regions. A number of alternative rules for the allocation of emission permits have been proposed. Gupta et al. (2007) and den Elzen and Höhne (2008) have provided meta-analyses of the resulting emission reduction obligations for Annex I and non-Annex I countries. The following four stylized burden-sharing rules were considered:

1. **Contraction and Convergence (C&C):** The C&C scheme (Meyer 2000) envisages a smooth transition of emission shares from status-quo (emissions in 2005) to equal per capita emissions in 2050. It combines elements of grandfathering–allocation based on current emissions–and equal per capita emissions. Therefore, it can be considered a compromise between a pure egalitarian regime and a grandfathering approach. This scheme was used in the default policy scenario discussed by Luderer et al. (2011).
2. **Common but differentiated convergence (CDC):** Similar to C&C, the CDC scheme (Höhne et al. 2006) also envisages a long-term transition from status-quo to equal per capita emissions. In order to account for historic responsibility, reductions targets that are more stringent are implemented for industrialized countries as compared to C&C, resulting in per-capita allocations below the world average after two decades. Countries that do not belong to Annex I of the UNFCCC receive allocations according to their business-as-usual trajectory until their emission allocation is more than 20 % above global average per-capita emissions. After crossing this "graduation threshold," per-capita allocations converge within 40 years to the level of the industrialized countries.
3. **GDP shares:** Emission allowances are allocated in proportion to GDP shares for each time step, i.e. identical numbers of emission permits per unit of GDP. This scheme can also be interpreted as an intensity-based regime, in which countries with low emissions intensity of GDP benefit, while countries with high emissions intensity are penalized. As shown in Section 3.2, this allocation scheme is highly disadvantageous for developing countries. It also results in extremely unequal per capita emission rights. Thus, it is clearly at odds with the UNFCCC principle of common, but differentiated responsibility. Therefore, it should be considered a purely exploratory allocation scheme, but not a reflection of a realistic political outcome.
4. **Global tax regime:** A uniform global tax with national recycling of revenues is imposed. Since it also results in the equalization of marginal abatement costs in all regions, it represents a special case of an efficient international climate policy regime without financial transfers between nations. In the absence of uncertainty, it is equivalent to an emissions trading scheme in which the allocation corresponds to the optimal regional abatement level, such that, net trade-balances are zero for all regions. It implicitly assumes a burden-sharing scheme in which emission reduction obligations are distributed according to mitigation potential.

Climate policy is assumed to be enacted from 2010 onwards. In the analysis, the reduction targets emerge endogenously from the burden-sharing assumptions and regional emission reduction potentials. For the sake of conceptual clarity, neither Kyoto targets nor the Copenhagen Pledges are taken into account.

In order to quantify the costs of climate policy, we compare macro-economic consumption levels in the policy scenarios to a reference scenario without climate policy (baseline). For the entire analysis presented in this paper, a 5 % discount rate is used for the inter-temporal aggregation of consumption losses. In this study, we consistently use these inter-temporally aggregated consumption losses as a metric for total mitigation costs. They include permit revenues or expenses.

Due to the scientific uncertainty about the size of climate change impacts and about their evaluation in financial terms and over time, they are not part of this analysis. Therefore, the model results should not be interpreted as a cost-benefit-analysis, but rather as a cost-effectiveness analysis of the economics of reaching the prescribed climate target.

3 Results

3.1 The global perspective

This section presents the findings of the models with respect to the global-level macro-economic effects induced by climate policy. Luderer et al. (2011) provide a more detailed analysis of the results for the baseline and C&C climate policy scenario, the future development of energy systems and carbon prices, as well as the differences across models.

Figure 1 shows the CO_2 emissions from fossil fuel combustion in the baseline scenario and the policy scenarios that strive to stabilize atmospheric CO_2 concentrations at 450 ppm. The IMACLIM-R baselines feature the lowest long-term CO_2 emissions, with a cumulative total of 4,700 $GtCO_2$ from 2005 to 2100. This is largely due to the strong reduction of energy intensity in response to increasing fossil resource prices. The ReMIND-R baseline features a strong, fossil-based expansion of the energy system until 2050, followed by a period of efficiency increases and the phasing-in of carbon-free energy carriers in response to the increasing scarcity of fossils. Consequently, emissions increase steeply over the course of the first half of the century and stabilize thereafter. The cumulative total emissions from 2005 to 2100 amount to 6,300 $GtCO_2$. The primary energy demand in the WITCH baseline is slightly lower than in the other two models and continues to be based on fossils throughout the century, with only marginal contributions of carbon-free energy carriers to the primary energy supply. Emissions increase monotonically throughout the 21st century, with cumulative CO_2 emissions of 5,900 $GtCO_2$.

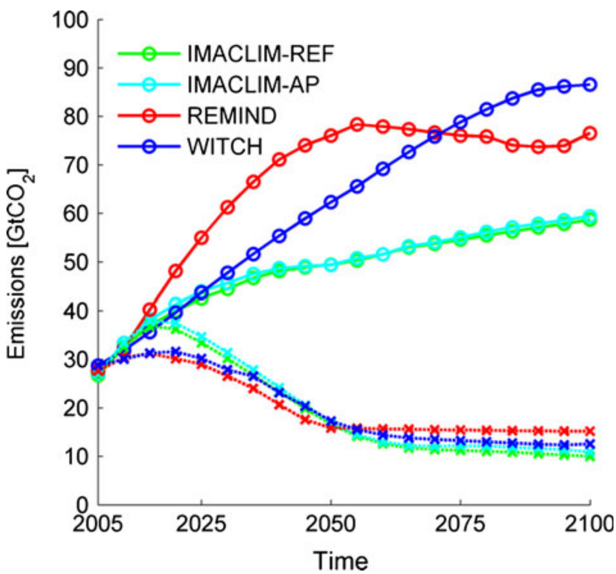


Fig. 1 Global pathways for CO_2 emissions from fossil fuel combustion for the baseline scenario as well as policy scenarios aiming at the stabilization of atmospheric CO_2 concentrations at 450 ppm

The gap between baseline emissions and the emission trajectories for the policy scenarios demonstrates the scale of the mitigation challenge. Introducing a stabilization target on CO_2 concentrations reduces cumulative emissions between 2005 and 2100 to less than 2,000 Gt CO_2, which corresponds to 30–40 % of baseline emissions. Emissions in 2050 are reduced by about 40 % relative to 2005 levels. Emissions reductions are achieved through a combination of energy efficiency improvements and a decrease of carbon intensity in the energy mix, i.e. by shifting towards low-carbon energy carriers such as renewable sources, carbon capture and storage (CCS), and nuclear power. However, such a transformation of the energy system will not occur without economic incentives. By pricing the negative externality associated with the use of fossil fuels, the carbon price emerging from a global carbon market could provide the proper incentive and increase the economic attractiveness of cleaner alternatives that would not be competitive otherwise.

For the further analysis, it is important to note the considerable variance in model results with respect to the economic effects of climate policy. While the carbon price is independent of the allocation scheme in each model, the price trajectories differ substantially across models. In the perfect foresight models, ReMIND-R and WITCH, the CO_2 price increases gradually after the onset of climate policy (Fig. 2). In ReMIND-R, it reaches a maximum slightly above 100\$/tCO_2 in 2050 and once atmospheric CO_2 concentrations have stabilized, remains in a range of 50–100 US\$/tCO_2. This comparatively low carbon price reflects the high degree of technological flexibility in ReMIND-R and the decrease in costs of low-carbon technologies due to technological learning. Mid- and long-term carbon prices in WITCH are much higher than in ReMIND-R and exceed 1,000 US\$ by 2080. This is due to more pessimistic assumptions about technological flexibility and opportunities for substitution within the energy system (Luderer et al. 2011; Tavoni et al. 2011). In WITCH, substantial R&D activity is needed before the deployment of zero-carbon alternatives becomes competitive. Consequently, a higher carbon price is required to induce sufficient R&D investments. Due to the assumptions of imperfect foresight in IMACLIM-R, much higher carbon prices are initially required to create a sufficiently strong signal to myopic agents, in order to trigger a transition to a low-carbon energy system, in comparison to the other two models (Fig. 2). After 2030, the carbon prices in the IMACLIM-AP scenarios are considerably lower than in the IMACLIM-REF scenarios, due to more optimistic assumptions about ancillary labor and infrastructure policies that increase flexibility and support the

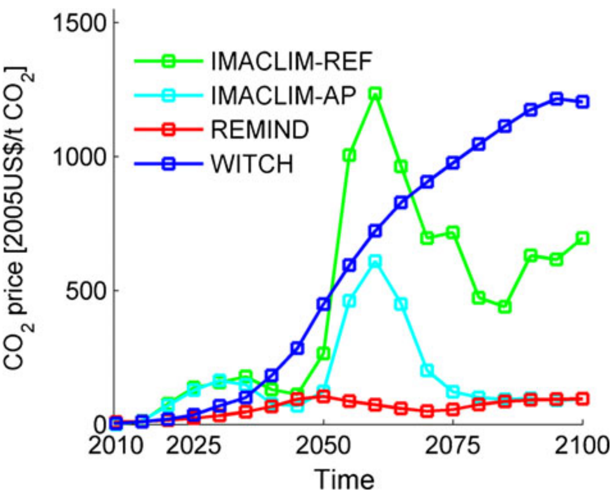


Fig. 2 Global carbon prices for the C&C climate policy scenario aiming at the stabilization of atmospheric CO_2 concentrations at 450 ppm

low-carbon transition. Both sets of IMACLIM-R scenarios have a distinct peak in CO_2 prices after 2050. The high carbon prices are required to avoid deployment of coal-to-liquid technologies–which are highly carbon-intensive–in times of increasingly scarce oil and of increasing mobility demand.

The range of carbon prices in RECIPE for 2020 is 16–76 \$/tCO_2. This range compares well with the carbon price range of 10–52 \$/tCO_2 from the 3.7 W/m² stabilization scenarios considered in EMF-22, which are slightly less ambitious than our 450 ppm CO_2 stabilization target (Clarke et al. 2009).

Figure 3 shows the temporal development of globally aggregated consumption losses. In WITCH, climate change mitigation leads to significant reductions of economic output, particularly in the second part of the century. Consequently, global consumption losses relative to baseline consumption increase almost monotonically until 2070 and decline afterwards, largely due to the long-term benefits of low-carbon innovations. In ReMIND-R, the highest losses occur before 2050, the time of highest emission growth in the baseline. The lower long-term losses in ReMIND-R are largely a reflection of more optimistic assumptions for low-carbon technologies on the energy supply side and higher flexibility in switching between different energy carriers (Luderer et al. 2011).

Following the Coase theorem (Coase 1960), the global costs of climate policy under an emissions trading regime are independent of the allocation scheme, provided there are no

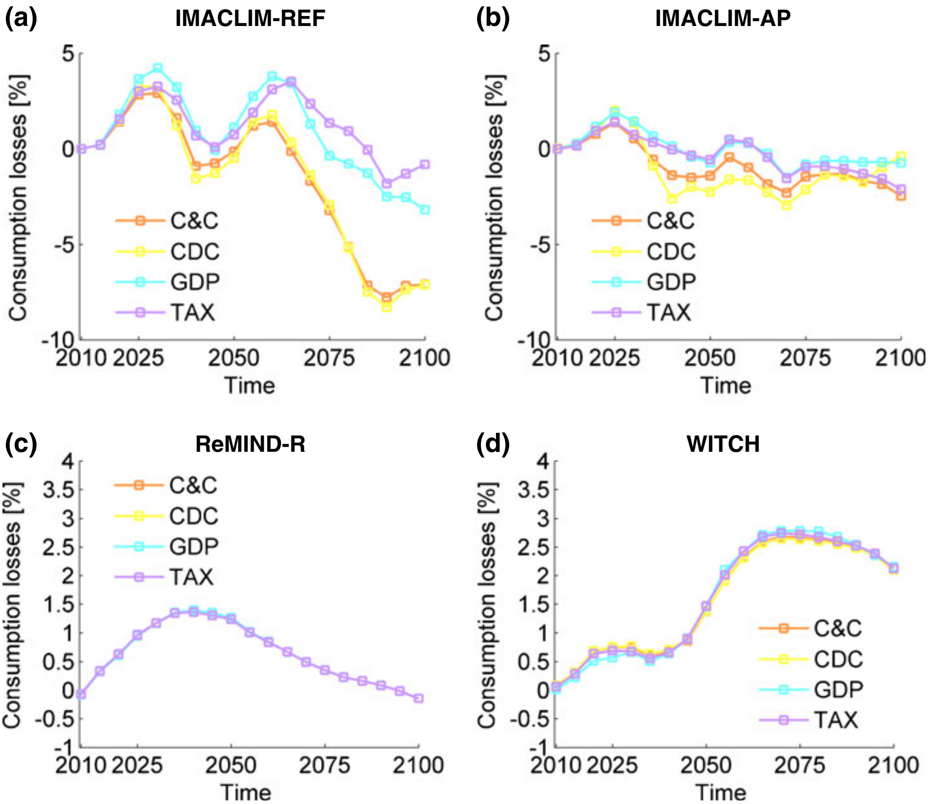


Fig. 3 Development of global mitigation costs in terms of consumption differences (**b**–**d**) relative to baseline as computed by the three models

other non-internalized externalities or market failures. This tenet holds strictly for ReMIND-R. In WITCH, slight variations exist between allocation schemes (Fig. 3c) because the non-internalized externality of technological spillovers results in different patterns of R&D expenditure for the different allocation schemes. In contrast, the allocation of emission permits on global mitigation costs has a pronounced effect in both sets of IMACLIM-R scenarios. In this model, the sensitivity of economic development to carbon market transfers is higher in non-Annex I than in Annex I countries (cf. Section 3.4). Therefore, burden-sharing schemes with lower allocations for developing countries result in higher global mitigation costs than burden-sharing schemes with relatively higher allocations for developing countries.

IMACLIM-R projects high transitory consumption losses resulting from climate policy with a first peak of mitigation costs occurring between 2025 and 2030. A second cost maximum emerges around 2060, which is related to the maximum observed in the carbon prices. The economy's sensitivity to climate policy depends strongly on the policy assumptions. In the reference case (Fig. 3a), short- and medium-term consumption losses are much higher than in the case with ancillary labor and infrastructure policies, which results in higher flexibility (Fig. 3b). However, in the long-term, the stimulus to developing country economies, which arises from higher carbon market transfers in the C&C and CDC scenarios, results in higher aggregate global consumption gains in IMACLIM-REF, compared to IMACLIM-AP.

3.2 Allocation of emission permits

Figure 4 depicts the regional cumulative CO_2 emissions calculated by the models for the baseline and climate policy scenarios. The models consistently show that in the baseline, more than half of the emissions would originate from non-Annex I countries. Under climate policy, all regions reduce their emissions by at least 50 %, relative to baseline. Baseline emissions are highest in ReMIND-R; therefore, the required emission reductions are larger than in the other models. The models find that the relative emission reductions in India and the other developing countries tend to be higher than in the industrialized countries and China.

The existence of a global carbon market in the climate policy scenarios gives rise to a dichotomy between the initial endowment (allocation) of emission permits and actual emissions after emissions trading has occurred. Countries that emit less than their endowment can sell permits, while regions with higher emissions have to buy them.

Figure 5 shows how the allocation of emission allowances under different burden-sharing schemes compares to baseline emissions, for 2020 and 2050. The scenarios chosen cover a considerable range of possible outcomes. While the allocations relative to the baseline emission levels are similar across the models, some differences exist due to different baseline emission levels, differences in the definitions of regions, and different regional patterns of economic growth in the case of the GDP-shares-allocation scheme.

For C&C and CDC, the two burden-sharing rules that envisage the long-term convergence of per-capita emission permits–emission allocations to India and other non-Annex 1 countries–are close to baseline emissions. All the models except ReMIND-R project C&C to result in an over-allocation of permits for India and R-nA1 in 2020. The allocations of emission permits in 2050 under CDC and C&C correspond to reduction targets of 7–33 % relative to baseline for India, and 38–67 % for R-nA1. By contrast, the allowance allocations for the GDP and TAX scenarios are much lower and correspond to reduction targets of 65–87 % below baseline in 2050 for IND and R-nA1. GDP and TAX also result in substantial near-term (2020) reduction obligations.

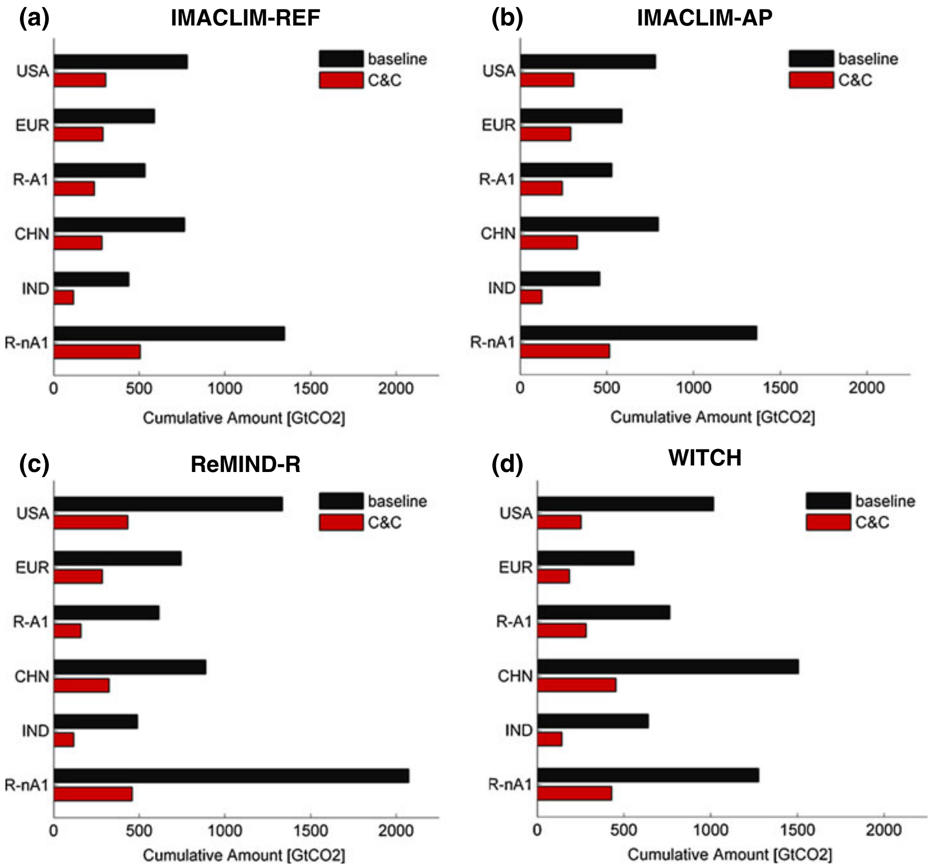


Fig. 4 Regional fossil fuel-related CO_2 emissions cumulated from 2005 to 2100, for the baseline and the C&C climate policy case. Regional cumulative emissions for the other climate policy scenarios are nearly identical, and therefore, are not shown

The situation is opposite for the industrialized countries. For them, C&C and CDC imply the highest reduction targets. For the US, 2050 allocations are a mere 5–8 % of baseline emissions for C&C and 4 % for CDC. For Europe and R-A1, 2050 reduction targets relative to baseline are between 82 and 95 %. The 2050 allocations for C&C and CDC are roughly consistent with the 80–95 % reduction target relative to 1990 found by den Elzen and Höhne (2008). In ReMIND-R, which is characterized by strong near-term emission increases in the baseline, CDC implies reductions of 71 % and 65 % relative to baseline levels in 2020 for the US and Europe, respectively, while the other two models project 40–46 % (USA) and 33–35 % (EUR). The GDP and TAX scenarios provide much more leeway for the industrialized countries, with much lower long-term reduction targets and even considerable over-allocation in excess of the baseline emissions projected by some models for the GDP scenario in 2020.

All of the burden-sharing schemes considered in this study imply significant long-term reduction obligations for China, with 2050 permit allocations between 13 and 35 % of baseline emissions. For 2020, the C&C burden-sharing rule requires 6–28 % emission reductions relative to baseline. Even the CDC rule, which is designed to provide some leeway for developing countries in the short- to medium-term, 2020 reduction targets will be

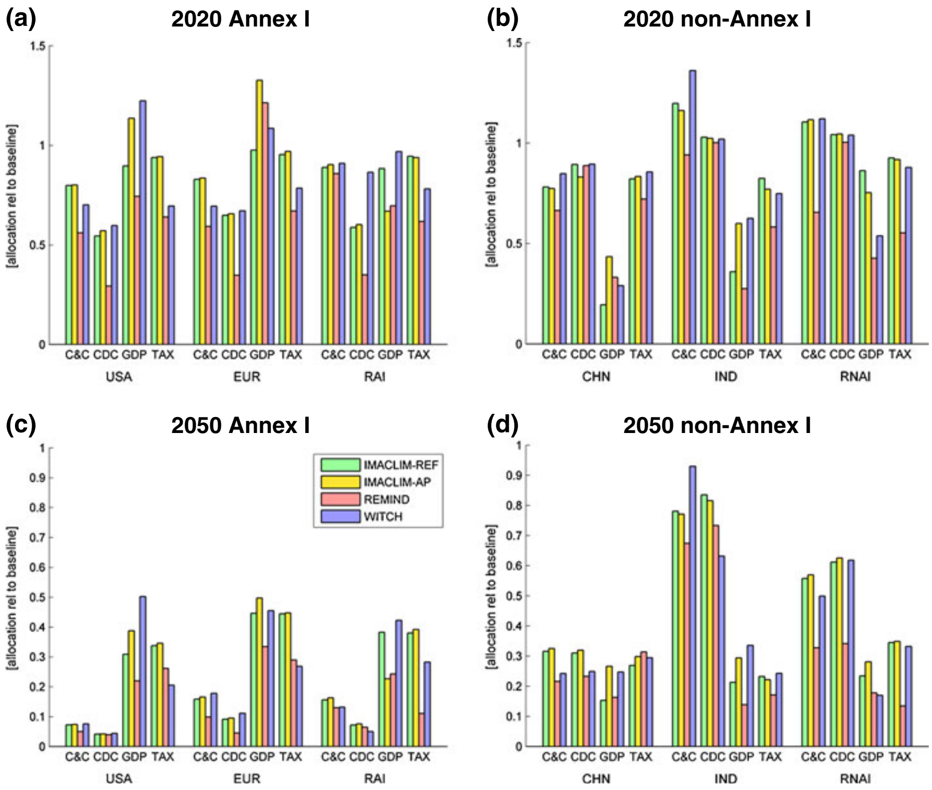


Fig. 5 Allocations of emission permits relative to baseline emissions for the four burden-sharing rules considered, for 2020 (**a**, **b**), and 2050 (**c**, **d**)

about 10 % below baseline. According to the GDP scenario, drastic emission reductions will be imposed on China, particularly in the near-term. The relative emission reductions implied by the TAX scenario are comparable to those of the C&C scenario, for 2020 and 2050.

3.3 Regional distribution of costs

Figure 6 shows the global (WORLD) and regional total mitigation costs, expressed in terms of the net present value of aggregated consumptions losses, as well as the regional costs for 2020 and 2050. The colored bars show the mitigation costs for the tax regime. Since it is the only scenario with efficient climate policy in the absence of financial transfers, it can serve as a reference case against which to compare the cap-and-trade scenarios with explicit allocation of emission permits (black symbols).

The inter-regional variance in relative mitigation costs for the tax regime is smaller than for the other schemes. For ReMIND-R, the regional costs are below 1.1 % for all regions, and below 2.2 % for WITCH. For both models, no region obtains net gains from climate policy under the tax scheme. By contrast, the tax regime in IMACLIM-REF incurs high losses for China at 10 %, while the USA and EU experience net gains. In IMACLIM-AP, the presence of ancillary policies tends to decrease the consumption losses or increase the gains induced by climate policies in all the world regions with the exception of India, which has higher long-term benefits in the IMACLIM-REF scenario.

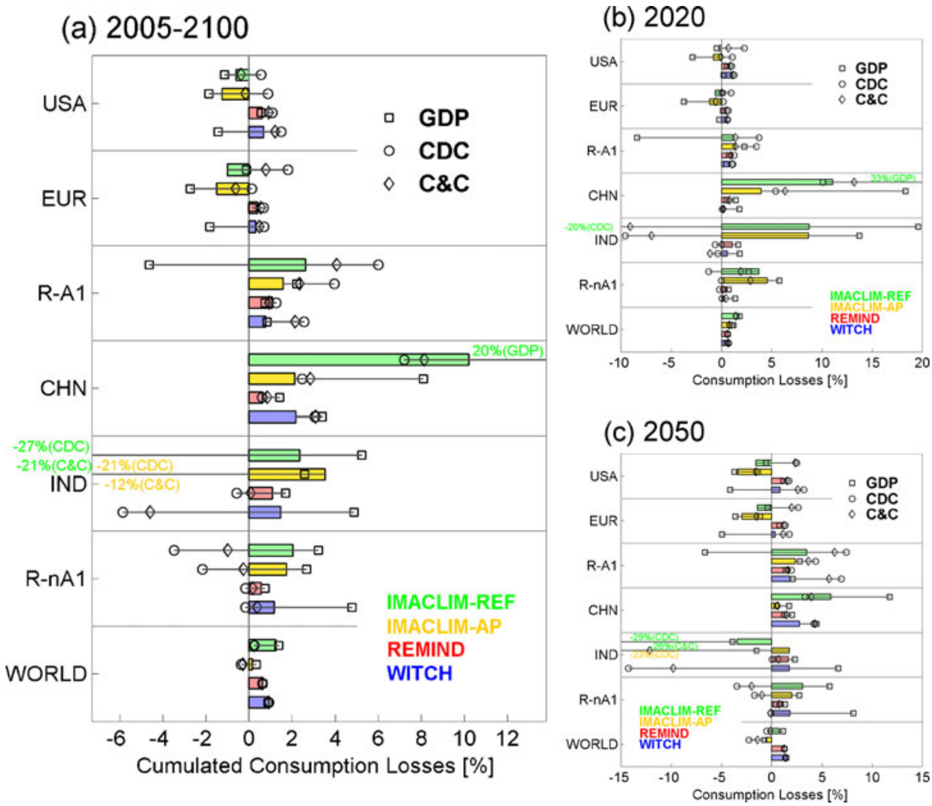


Fig. 6 Regionalized consumption losses (**a**) aggregated for the time period 2005–2100 by region, using a discount rate of 5 %, (**b**) for 2020, and (**c**) for 2050. The *colored bars* show mitigation costs with efficient climate policy (global uniform carbon price) in the absence of financial transfers (tax regime). *Symbols* show losses for the other three allocation schemes C&C, CDC, and GDP shares, and *lines* indicate the spread across burden-sharing schemes. Positive values correspond to consumption losses, while negative values indicate gains. Outliers are listed separately

Under the other three cap-and-trade regimes, the regional distribution of costs varies more widely, and regional costs deviate substantially from the global mean in many cases. In line with the pattern of permit endowments, the models show a consistent ranking of welfare effects for the burden schemes. Industrialized countries would fare best with the GDP-shares scheme, while C&C and CDC result in the highest costs. Due to their strong economy with relatively low emissions-per-unit GDP, losses of the EU and the USA are projected to be below the world average for the GDP shares allocation. By contrast, India and R-nA1are characterized by low per-capita emissions and therefore, would benefit from the long-term allocation of permits in terms of equal per capita emission rights, as compared to the tax regime. Thus, the CDC scheme is most advantageous and results in net gains for these countries in all of the models.

The situation for China is distinctly different. For all of the allocation schemes, the models project above world average consumption losses. Currently, China's per capita emissions are roughly equal to the world average. Almost all of the scenarios and models, project China to be a net-buyer of emission permits for most of the first half of the century due to their highly emission-intensive growth trajectory; this is also true for the policy scenario. Consequently, the tax regime with full national recycling of revenues from carbon pricing remains the least costly option for China, according to ReMIND-R, WITCH, and IMACLIM-AP.

Despite some common conclusions, the regional distribution of mitigation costs and the spread between different allocation schemes vary substantially across models. This is largely due to different representations of the energy system, macro-economic inertias, trade, and, to a minor extent, the regional patterns of economic growth assumed in the baseline.

The two sets of IMACLIM-R scenarios exhibit a very high sensitivity of mitigation costs to the allocation rule, particularly for China and India. As further elaborated in Section 3.4, this sensitivity is due to (a) relatively high carbon prices, especially in the near–term and (b) the presence of strong macro-economic multiplier effects arising from the effects of carbon trading on households' purchasing power. This sensitivity is generally larger for IMACLIM-REF than for IMACLIM-AP, chiefly because carbon price levels are higher in IMACLIM-REF.

Under the CDC scheme, gains for India can be as high as 21 % (IMACLIM-AP) to 27 % of macroeconomic consumption (IMACLIM-REF), which would imply severe losses in the case of the GDP or TAX burden schemes, particularly in the near-term. IMACLIM-REF reports very high mitigation costs for China, ranging from 7 % (CDC) to 20 % (GDP shares). With the exception of the GDP shares scenario, the inter-temporally aggregated costs for China are below 3 % in IMACLIM-AP.

According to the WITCH model, the GDP shares regime would result in substantial consumption losses for developing countries, in the order of 4 % and 5.5 % for India and China over 2010–2100, respectively, while the EU and USA would enjoy net gains. India is projected to be a significant beneficiary of the C&C and CDC regimes with increases of aggregated consumption of 5 % and 6 %, respectively. Losses in the EU are below world average for all four scenarios; while they are projected to be about double the world average for China, e.g. up to 4.5 % for the C&C and CDC scenarios.

Both WITCH and IMACLIM-R find that burden-sharing rules have a strong effect on regional mitigation costs both across and within regions. However, in ReMIND-R, the costs are more evenly distributed across regions, and differences across burden-sharing regimes are smaller for single countries. "Worst-case" regional costs are also significantly smaller than in the other models, with no region experiencing losses above 2 % in any of the policy scenarios. The EU's losses are close to the global average for C&C and CDC, while GDP shares and the tax regime would imply mitigation costs below the world average. US losses are projected to be slightly higher than those of the EU, with similar dependence on the allocation rule. Even in the case of CDC—the most favorable for China among all the allocation schemes considered–and the tax regime, China's consumption losses exceed the global average. India and other non-Annex I countries are projected to have net gains from climate policy for the CDC regimes. GDP shares and the tax regime would result in above world-average mitigation costs in all three macro-regions of the developing world.

Due to the inter-temporal adjustments of saving rates, mitigation cost patterns for 2020 and 2050 are similar to the 2005–2100 aggregate.

3.4 The role of allocation rules vs. domestic abatement costs

The results of the model inter-comparison show that the effect of burden-sharing rules on regional consumption losses is very different across models, with particularly large spreads for IMACLIM-REF, IMACLIM-AP and WITCH, and rather small spreads for ReMIND-R. This points to the dominant influence of carbon prices on the sensitivity of regional costs to differences in allocation rules: the higher the carbon prices, the higher the monetary transfers associated with the trade of a given number of emission permits. Figure 7 visualizes the nexus between carbon trade and mitigation costs in terms of consumption losses. It relates the net present value of regional consumption losses to the future stream of carbon trade costs, i.e. the net present value of the aggregated expenditure for emission permits.[1] Negative carbon trade costs correspond to exports of emission permits, while positive carbon trade costs correspond to imports. For all the models and regions, we find a monotonic and almost linear decrease of mitigation costs with the increasing export of emission permits.

This linear functional relationship makes it possible to separate the effect of the allocation of emission permits from effects related to domestic abatement costs and the revaluation of natural resources due to changes in demand, which would occur in response to climate policy. We can approximate the net present value of a region's consumption losses, CL_r, as the sum of aggregated domestic costs DC_r and the carbon trade costs CTC_r

$$NPV(CL_r) \approx NPV(DC_r) + c_r NPV(CTC_r), \tag{1}$$

where CTC_r relates to the inter-temporally aggregated expenditures for emissions trading, which are positive for the net import of permits and negative for permit export. The coefficient, c_r, describes the slope of the correlation. The domestic costs, DC_r, account for all costs other than those related to carbon trade. Domestic costs are comprised of adjusting the domestic energy system, as well as the effects of the changing prices of tradable energy carriers.

For the inter-temporal optimization models, ReMIND-R and WITCH, the nearly full-scale separability of the allocation effects from the other cost factors is illustrated by the tight correlation between the carbon trade balance and the mitigation costs, and a parameter value of c_r that is close to one. For a given global stabilization target, the amount of emission reductions performed in a region and the cost of doing so are almost entirely independent of the amount of emission allowances allocated. This result is driven by the worldwide harmonization of marginal abatement costs that occurs when a well-functioning international carbon market is in place, and in line with previous findings in the literature (Manne and Stephan 2005). For a given global mitigation target, the allocation of more emission allowances for a region simply results in an increase in the region's revenue from selling emission permits to other regions, or in reduced expenditure for purchasing permits. Likewise, as discussed in Section 3.1, the carbon price path is only determined by the global mitigation target, but is independent of the allocation rule.

A notable feature of the separability of equity and efficiency is that the domestic cost components are simply a function of the global mitigation target, but not of the allocation rule, while the carbon trade balance only depends on the allocation rule and the carbon price path. However, for WITCH, different regional allocation schemes might slightly change the incentive to invest in abatement options by modifying the carbon budget assigned to each region. De Cian et al. (2011) show that developed countries' investments in energy R&D slightly increase in the short-term when these regions are allocated fewer permits (in the CDC case). This is due to the fact that regions do not cooperate in their R&D efforts, thus, the WITCH outcome slightly deviates from the Pareto-optimal (cooperative) outcome. However, this effect is modest and only transitory in nature. Therefore, the domestic cost component can also be considered nearly allocation-independent in the WITCH model.

For both ReMIND and WITCH, the coefficients, c_r, in Eq. (1) are close to unity; therefore, each additional dollar of carbon trade revenue results in approximately one dollar

[1] Both consumption losses and carbon trade costs are discounted at 5 % p.a.

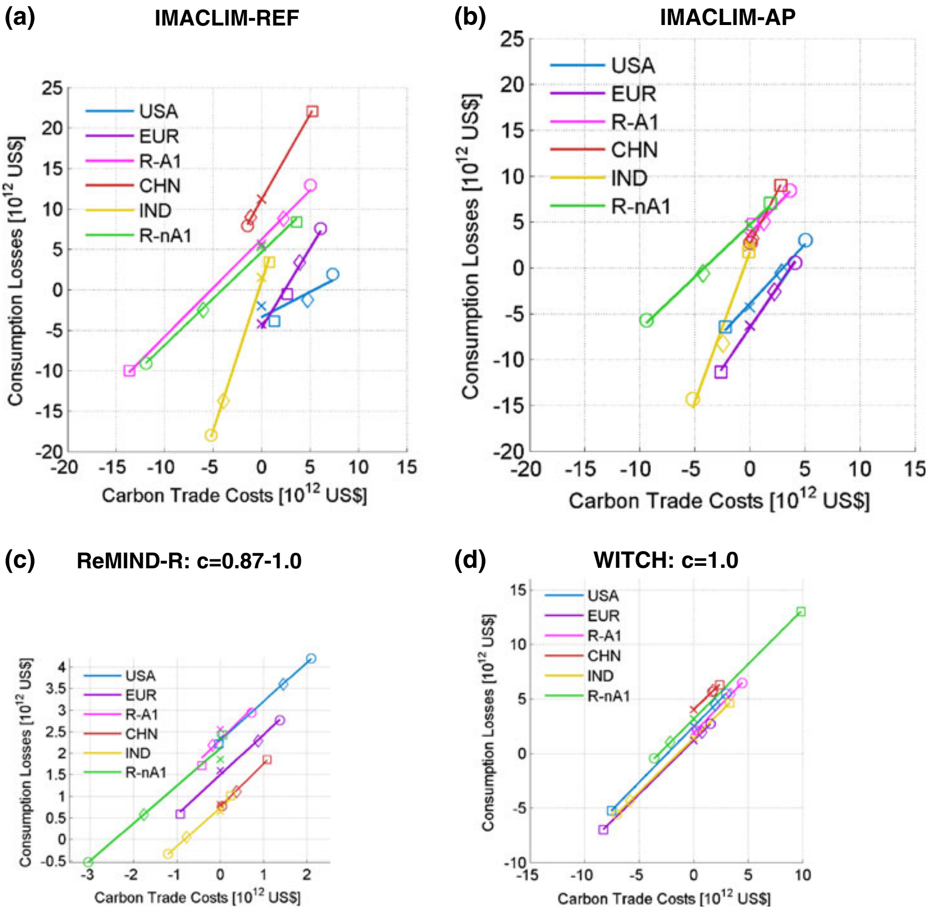


Fig. 7 Discounted consumption losses vs. discounted carbon trade costs for WITCH, ReMIND-R, and IMACLIM-R. Symbols indicated different allocation schemes C&C (*white diamond*), CDC (*white circle*), GDP shares (*white square*), and TAX (*multiplication sign*). Note the different scale for panel (**b**). A 5 % discount rate was used for the inter-temporal aggregation

of consumption gain because the revenue from emission permits increases the budget available for consumption. While IMACLIM-R also displays a strong correlation between carbon trade volume and regional mitigation costs, the value of the c_r-coefficient varies strongly across regions and deviates substantially from one for most regions. The highest values are attributed to China ($c_{CHN} = 2.8$) and India ($c_{IND} = 2.3$), and values between 0.97 and 1.5 are found for the other regions. The higher c_r-values translate into higher sensitivity of the mitigation costs to carbon trade costs. The underlying mechanism is two-fold: large carbon imports have to be balanced by higher exports of goods; this leads to lower terms of trade, which induces a loss of purchasing power of households and, ultimately, adds to the direct losses incurred from carbon trade. This terms-of-trade effect is amplified by a macro-economic multiplication effect: the lower purchasing power of wages leads to lower demand from households and lower economic growth. The effects are reversed for the export of permits. The financial transfers associated with permit trade relative to the total consumption are highest in China and India, which results in the highest amplification factors.

These effects are not present in the optimization models, ReMIND-R and WITCH. WITCH does not represent international trade. The flexibility of adjusting regional investments and global capital flows in ReMIND-R avoids the negative feedback effects observed in IMACLIM-R.

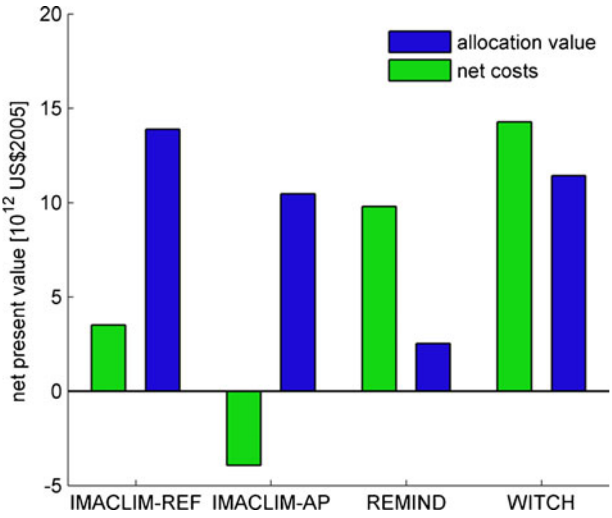
Table 1 presents the decomposition of regional mitigation costs in the three models for the C&C scenario. Due to the complex macroeconomic feedback effects in IMACLIM-R, it is not possible to identify the domestic cost component for this model. For the IMACLIM scenarios, the net present value of global consumption losses for the C&C scenario aggregated until 2100 and discounted at 5 % amounts to 3.5 Trn USD2005 for IMACLIM-REF and −3.5 Trn USD2005 (gains) for IMACLIM-AP. ReMIND-R and WITCH find losses of 9.8 and 14.3 Trn USD2005, respectively. Estimates of regional costs vary markedly across the models, ranging from multi-trillion USD2005 losses in industrialized countries and China to substantial gains for India, as projected by WITCH and the IMACLIM scenarios. In WITCH and ReMIND-R, the domestic costs are positive for all regions. Due to the low carbon price, the net present value of the carbon trade balance is small in ReMIND-R compared to the other models. Consumption losses are, therefore, dominated by domestic costs. In contrast, higher carbon prices lead to much higher financial carbon trade volumes in WITCH and IMACLIM-R, which results in a much larger effect of carbon trade on regional mitigation costs.

Figure 8 provides a further illustration of the difference in the significance of allocations for regional mitigation costs across models, which depicts the discounted permit allocation value—i.e. the cumulative net present value of all emission permits that would be allocated over the course of the 21st century under the 450 ppm CO_2 target–and compares it to the discounted net mitigation costs. The discounted allocation value serves as an indicator of the value at stake in the bargaining for an international burden-sharing agreement under a global emissions trading system. In IMACLIM-REF, it amounts to 13 trn USD (1.2 % of global

Table 1 Decomposition of net regional consumption losses (CL) for the contraction and convergence burden-sharing scheme into domestic costs (DC) and carbon trade costs (CTC), which depends on the allocation rule. By convention, carbon trade costs are positive for the net import of emission permits, while the net export of permits results in negative carbon trade costs. All figures are net present values discounted at 5 %. Due to the complex macro-economic feedback effects, it was not possible to single-out domestic costs for the IMACLIM scenarios

	10^{12} USD_{2005}	USA	EU	Rest of Annex-I	China	India	Rest of non-Annex-I	World
IMACLIM-REF	$NPV(DC_r)$	–	–	–	–	–	–	–
	$NPV(CTC_r)$	4.8	4.0	2.3	−1.1	−3.9	−6.0	0.0
	$NPV(CL_r)$	−1.2	3.3	8.8	8.9	−13.8	−2.5	3.5
IMACLIM-AP	$NPV(DC_r)$	–	–	–	–	–	–	–
	$NPV(CTC_r)$	2.9	2.2	1.3	0.2	−2.4	−4.2	0.0
	$NPV(CL_r)$	−0.6	−2.6	5.0	3.2	−8.3	−0.7	−3.9
REMIND-R	$NPV(DC_r)$	2.3	1.6	2.5	0.8	0.6	1.9	9.8
	$NPV(CTC_r)$	1.5	0.9	−0.2	0.4	−0.8	−1.8	0.0
	$NPV(CL_r)$	3.6	2.3	2.2	1.1	0.05	0.6	9.8
WITCH	$NPV(DC_r)$	2.5	1.2	2.0	4.0	1.4	3.2	14.2
	$NPV(CTC_r)$	2.0	0.8	3.4	1.8	−5.8	−2.1	0.0
	$NPV(CL_r)$	4.5	1.9	5.4	5.8	−4.4	1.0	14.3

Fig. 8 Aggregated global consumption losses (net costs) and global allocation values for the C&C scenarios. A 5 % discount rate was used for the inter-temporal aggregation



aggregated consumption), more than twice the net mitigation costs. In ReMIND-R, by contrast, the discounted allocation value is as low as 3.3 trn USD (0.2 % of aggregated consumption), which is about one order of magnitude lower than in IMACLIM-R and is substantially lower than the ReMIND-R projections of global mitigation costs. With a discounted allocation value of 11.4 trn USD (0.7 % of aggregated consumption), WITCH lies between the other two models and projects the allocation value to be of comparable magnitude to the global net mitigation costs.

4 Discussion and conclusions

A number of findings emerge from the inter-model comparison of regional mitigation costs. First, and most importantly, we find that regional mitigation costs may deviate substantially from the global average. While global costs were found to be in the range of −0.4 to 1.4 % of aggregated consumption or less, the two versions of the IMACLIM model, as well as the WITCH model, find that certain burden-sharing schemes result in regional costs in excess of 5 % for some regions, and considerable gains for other regions. Second, we find that the spread across models, as well as that across regions, tends to be smaller for the tax regime scenario than for those scenarios that involve transfers induced by the trade in emission permits. A tax regime results in positive aggregate mitigation costs for all regions in WITCH and ReMIND-R, and all regions of the developing world in the IMACLIM scenarios. Third, we find that mitigation costs in developing countries are much more sensitive to the applied burden-sharing rule than in industrialized countries. This is due to the relatively high carbon intensity of GDP in the developing world, which implies that climate policy costs account for a much larger share of economic output. Fourth, for all the burden-sharing schemes analyzed, we find that China would suffer above-world-average mitigation costs. In many cases, China would be better off with a regime based on globally harmonized carbon taxes compared to global emissions trading with the burden schemes considered here. The GDP-shares rule is extreme, as it implies very stringent near-term reduction targets for developing countries and, consequently, results in the highest mitigation costs for developing countries. Given the low historic responsibility and the relatively lower economic capacity of the developing countries, this burden-sharing scheme seems rather unrealistic as an outcome of climate negotiations. Consequently, very high mitigation costs emerge for developing countries. Finally, we find the effect of burden-sharing rules on regional mitigation costs to be very different across models, with largest spreads for IMACLIM-REF, followed by IMACLIM-AP and WITCH, and rather small spreads for ReMIND-R.

The decomposition of regional mitigation costs into domestic costs and the effects related to emissions trading provide insights into the main components of regional net mitigation costs. The large differences in the models' sensitivities to changes in the allocation rule can be explained by the significant differences of carbon prices. ReMIND-R is characterized by optimistic assumptions about technological and macro-economic flexibility; therefore, the climate target can already be achieved with a rather low carbon price. Consequently, the carbon trade-related component of regional mitigation costs is rather small. In contrast, WITCH, IMACLIM-AP, and IMACLIM-REF show much higher carbon prices. WITCH shows higher carbon prices because of lower technological flexibility, and the IMACLIM versions because of imperfections and rigidities in the economic system, as well as the nature of the decision process, which is based on imperfect foresight. Therefore, emissions-trading results in higher financial transfer volumes, which makes these two models more sensitive to the allocation of emission permits. In the IMACLIM scenarios, terms-of-trade effects and other macro-economic feedbacks further amplify the consumption effects of carbon trade.

Our results bear several important implications for climate policy. First, they document the considerable uncertainty about the regional distribution of climate policy costs. This uncertainty may constitute a major obstacle for long-term commitments from nations towards global cooperative mitigation action. This is an important argument in favor of implementing an adaptive burden-sharing mechanism in which the regional distribution of emission rights is adjusted over time rather than a policy framework that determines emission allocations now for a long-term future (such as the budget approach proposed by the German Advisory Council on Global Change, WBGU 2009). In the medium term, significant progress in climate-economic research is required to provide a sound basis for decisions by policymakers and negotiators.

Second, they show that certain regions, particularly in developing countries and emerging economies, may suffer prohibitively high mitigation costs, unless burden-sharing schemes are designed to compensate domestic costs with revenues from carbon trade, or other forms of side payments. Our results suggest that China has little interest in global emissions trading with any of the allocation rules considered, compared to a global tax regime without any carbon market transfers. This distinguishes it from less advanced developing countries, and puts it into a similar position as the Annex-I countries–with the notable exception of the GDP shares allocation, which is also disadvantageous for China, but not for Annex-I.

The third implication is that an international carbon market bears the potential of substantial rent transfers. This is because average abatement costs are considerably smaller than marginal costs of abatement, which determine the global carbon price. We estimate the net present value of allocated emission permits under the 450 ppm mitigation target to be between 3.3 and 13.3 trillion USD over the course of the 21st century.

Finally, the ability of societies to adjust energy systems and infrastructure towards low-carbon economies, as well as the degree of anticipation for future changes are crucial drivers for the carbon price required to meet a pre-determined mitigation target. The two alternative IMACLIM versions demonstrate the relevance of ancillary labor markets and infrastructure policies in reducing the adverse economic effects that arise from carbon pricing. Moreover, fostering R&D and the diffusion of low-carbon technologies can reduce the marginal CO_2

abatement costs. Such policies will not only reduce long-term mitigation costs, but also result in lower carbon prices, thus reducing the bargaining volume and potential rents arising from the allocation of emission permits.

Due to the complexities of the regional distribution of climate change mitigation costs and the heterogeneities across modeling approaches, we had to restrict ourselves to a set of stylized allocation rules regarding the assumption of an immediate setup of an international climate policy regime and uniform global carbon pricing. In order to add policy realism, further analyses of regional costs and the role of permit allocations in scenarios that consider imperfections such as delayed and fragmented international climate policy regimes are required. This is particularly relevant in view of the current failure of governments to establish a comprehensive international climate policy architecture.

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